

VLA H53 α and H92 α line observations of the central region of NGC 253

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ABSTRACT

We present new Very Large Array (VLA) observations toward NGC 253 of the recombination line H53 α (43 GHz) at an angular resolution of $1''.5 \times 1''.0$. The free-free emission at 43 GHz is estimated to be ~ 100 mJy, implying a star formation rate of $\sim 1.3 M_{\odot} \text{ yr}^{-1}$ in the nuclear region of this starburst galaxy. A reanalysis is made for previously reported H92 α observations carried out with angular resolution of $1''.5 \times 1''.0$ and $0''.36 \times 0''.21$. Based on the line and continuum emission models used for the $1''.5 \times 1''.0$ angular resolution observations, the RRLs H53 α and H92 α are tracers of the high-density ($\sim 10^5 \text{ cm}^{-3}$) and low-density ($\sim 10^3 \text{ cm}^{-3}$) thermally ionized gas components in NGC 253, respectively. The velocity fields observed in the H53 α and H92 α lines ($1''.5 \times 1''.0$) are consistent. The

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velocity gradient in the central ~ 18 pc of the NE component, as observed in both the H53 α and H92 α lines, is in the opposite direction to the velocity gradient determined from the CO observations. The enclosed virial mass, as deduced from the H53 α velocity gradient over the NE component, is $\sim 5 \times 10^6 M_\odot$ in the central ~ 18 pc region. The H92 α line observations at high angular resolution ($0''.36 \times 0''.21$) reveal a larger velocity gradient, along a P.A. $\sim -45^\circ$ on the NE component, of $\sim 110 \text{ km s}^{-1} \text{ arcsec}^{-1}$. The dynamical mass estimated using the high angular resolution H92 α data ($\sim 7 \times 10^6 M_\odot$) supports the existence of an accreted massive object in the nuclear region of NGC 253.

Subject headings: starburst galaxies, radio recombination lines, NGC 253

1. INTRODUCTION

NGC 253 is one of the nearest (~ 2.5 Mpc) and brightest starburst galaxies, catalogued as an SAB(s)c galaxy (de Vaucouleurs et al. 1976). This galaxy has an inclination of $\sim 79^\circ$ with respect to the line-of-sight with major axis located at a position angle (P.A.) of 51° , also containing a bar-like feature tilted by 18° with respect to the major axis (Pence 1981). Observations of NGC 253 have been carried out in the radio (Turner & Ho 1985; Ulvestad & Antonucci 1997; Mohan, Anantharamaiah, & Goss 2002; Mohan, Goss, & Anantharamaiah 2005; Boomsma et al. 2005) infrared (Engelbracht et al. 1998), optical (Forbes et al. 2000; Arnaboldi et al. 1995) and X-ray (Weaver et al. 2002) wavelengths. Radio observations, which are not affected by dust absorption, are an excellent tool to study the structure and kinematics of the nuclear region of NGC 253. Observations in the 21-cm line (Boomsma et al. 2005) reveal extra-planar motions of HI that occur at a large scale of up to 12 kpc. High angular resolution radio continuum observations (Ulvestad & Antonucci 1997) have revealed a number (> 60) of compact sources in the central 300 pc of this galaxy, supporting the scenario of a massive star formation episode occurring in the center of NGC 253. Nearly half of these compact continuum sources are dominated by thermal radio emission from HII regions (Turner & Ho 1985; Antonucci & Ulvestad 1988; Ulvestad & Antonucci 1997). The radio continuum and radio recombination line emission, observed at high angular resolution, have been modeled using different density components for the ionized gas (Mohan, Goss, & Anantharamaiah 2005). The emission models suggest the existence of both low ($\sim 10^3 \text{ cm}^{-3}$) and high-density ($> 10^4 \text{ cm}^{-3}$) ionized gas in the central region of NGC 253. On the other hand, the most luminous source (5.79-0.39) is unresolved (< 1 pc) at 22 GHz suggesting the existence of an AGN in the center of this galaxy (Ulvestad & Antonucci 1997). Observations of broad H₂O maser line emission ($\geq 100 \text{ km s}^{-1}$) near this radio continuum source has

been invoked as further evidence of the presence of a massive object in NGC 253 (Nakai et al. 1995). Mohan, Anantharamaiah, & Goss (2002) modeled the VLA continuum and radio recombination line (RRL) emission for the nuclear region of NGC 253 and favor an AGN as the source responsible for the ionization. Observations of hard X-ray emission toward the core of NGC 253 were also interpreted as evidence of AGN activity (Weaver et al. 2002).

The bar-like structure was first observed toward NGC 253 in the near-infrared (NIR), covering the inner $150''$ region of the galaxy (Scoville et al. 1985; Forbes & Depoy 1992). The existence of the stellar bar is supported by the observed morphology at optical and mid-infrared frequencies (Forbes & Depoy 1992; Piña et al. 1992). A counterpart of the stellar bar in NGC 253 has been found in CO (Canzian, Mundy, & Scoville 1988), HCN (Paglione, Tosaki, & Jackson 1995) and CS (Peng et al. 1996). Observations in the RRL $H92\alpha$ (Anantharamaiah & Goss 1996) at an angular resolution of $1''.8 \times 1''.0$ reveal a velocity field that is discrepant with the CO, CS and HCN observations. Anantharamaiah & Goss (1996) proposed that the kinematics observed in the $H92\alpha$ could result from a merger of two counter-rotating disks. The observed $H92\alpha$ and CO line velocity fields were modeled by Das, Anantharamaiah & Yun (2001) using a bar-like potential for NGC 253, which is in reasonable agreement with the observed $H92\alpha$ line velocity field. However, this kinematical model can only reproduce the velocity field of the CO and CS and does not agree with the $H92\alpha$ RRL observations. Based on the discrepancy of the CO and the ionized gas kinematics, Das, Anantharamaiah & Yun (2001) proposed that the accretion of a compact object ($\sim 10^6 M_\odot$) about 10^7 years ago could account for the velocity field observed in the $H92\alpha$ RRL. Paglione et al. (2004) observed the CO emission at $3''$ angular resolution for the inner region and modeled the kinematics of the molecular gas using a bar potential, concluding that motions of the CO gas in the central 150 pc are consistent with a bar potential and report evidence of the existence of an inner Lindblad resonance (ILR).

Previous interferometric observations of RRLs have been made at low frequencies (e.g. ~ 8.3 GHz, $H92\alpha$). VLA observations at $1''.5 \times 1''.0$ angular resolution were used by Anantharamaiah & Goss (1996) to study the kinematics of NGC 253; Mohan et al. (2002, 2005) used the VLA observations at $1''.5 \times 1''.0$ and $0''.3$ angular resolutions to determine the physical properties of the ionized gas in NGC 253. In this paper we analyse the kinematics of the ionized gas in the nuclear region of NGC 253 using high frequency RRL observations (~ 43 GHz) and the high angular resolution observations (at $0''.3$) in the RRL $H92\alpha$. Also we use the VLA observations in the RRL $H53\alpha$ and the 43 GHz radio continuum, along with previously reported $H92\alpha$ line and 8.3 GHz radio continuum observations (Mohan et al. 2005), in order to estimate the physical properties of the ionized gas. This paper is complementary to the results summarized by Mohan et al. (2005). Section 2 presents the observations and data reduction, while § 3 presents the results for the $H53\alpha$ and $H92\alpha$ RRLs.

In subsection 4.1, a model for the emission of the RRLs H53 α and H92 α as well as for the radio continuum at 43 and 8.3 GHz is presented. Subsection 4.2 analyzes the kinematics for the ionized gas in the center of NGC 253 and § 5 presents the conclusions.

2. VLA Observations.

2.1. H53 α line.

The H53 α line ($\nu_{rest} = 43309.4$ MHz) was observed in the CnD configuration of the VLA on 2003, January 18, 19 and 20. We used cycles with integration times of 10 min on NGC 253 and 1 min on the phase calibrator J0120-270 (~ 0.7 Jy). Four frequency windows (LOs) were used to observe the RRL H53 α , centered at 42885.1, 42914.9, 42935.1, and 42964.9 GHz. For each frequency window, the on-source integration time was ~ 2 hrs, using the mode of 15 spectral channels with a channel separation of 3.125 MHz (~ 22 km s $^{-1}$). The data calibration was carried out for each frequency window using the continuum channel, consisting of the central 75% of the band. The flux density scales were determined from observations of J0137+331 (3C48; 0.54 Jy). The bandpass response of the instrument was corrected using observations of J0319+415 (3C84; ~ 7.5 Jy). The parameters of the observations are summarized in Table 1. In order to track reliably the phase variations introduced by the troposphere, the calibration of the data was performed correcting for the phases in a first step and subsequently correcting for both amplitude and phase. The line data were further calibrated using the solutions obtained by self-calibrating the continuum channel of each frequency window. The radio continuum images were obtained by combining the continuum channels of each frequency window using the task DBCON from AIPS, and the self-calibration method was also applied to this combined data. The H53 α line cubes and the 43 GHz continuum image were made using a natural weighting scheme and then convolved to obtain a Gaussian beam of $1''.5 \times 1''.0$ (P.A. = 0°). The combination of the different frequency windows was made following a similar method to that used for the H53 α line observed toward M82 (Rodríguez-Rico et al. 2004): (1) the line data from each frequency window were regridded in frequency using the GIPSY reduction package, (2) before combining the four LOs into a single line cube, the continuum emission was subtracted for each frequency window using the AIPS task IMLIN with a zero order polynomial fit based on the line free channels, and (3) the four line cubes (after subtraction of the continuum) were combined into a single line cube. The total line bandwidth, after combining all the windows, is about 150 MHz (1000 km s $^{-1}$). The line data cube was Hanning-smoothed using the task XSMTH in AIPS to reduce the Gibbs effect and the final velocity resolution is ~ 44 km s $^{-1}$.

2.2. H92 α line.

We also present previously reported observations of the RRL H92 α ($\nu_{rest} = 8309.4$ MHz) at $1''.5 \times 1''.0$, P.A. = 0° (Anantharamaiah et al. 1996) and $0''.36 \times 0''.21$, P.A. = -3° (Mohan et al. 2005, 2002) angular resolutions toward NGC 253. The H92 α RRL images at $1''.5 \times 1''.0$ angular resolution were produced by combining observations carried out in the B (August 31 and Sept 01, 1990), C (May 14 and 23, 1988) and D (July 01 and 19, 1988) configurations of the VLA. In order to obtain the same HPFW beam as the H53 α line cube, the H92 α line cube was made using these 'B+C+D' combined data applying a natural weighting scheme. Anantharamaiah & Goss (1996) have already used these 'B+C+D' combined observations to analyze the kinematics of the ionized gas in the central $10''$ of NGC 253 with an angular resolution of $1''.8 \times 1''.0$, P.A. = 10° . The higher angular resolution ($0''.36 \times 0''.21$, P.A. = -3°) observations of the H92 α line toward NGC 253 were made with the VLA in the A array (July 9 and 12, 1999) and have been previously reported by Mohan, Anantharamaiah, & Goss (2002). Recently, Mohan, Goss, & Anantharamaiah (2005) used these H92 α data along with observations in the RRLs H75 α and H166 α data to model the RRL and the radio continuum emission in order to determine the physical parameters of the ionized gas. In this paper we use these high angular resolution observations to study the kinematics of the ionized gas in the nuclear $5''$ region of NGC 253. Because of the different spectral line grid of the H92 α high angular resolution observations and the H92 α 'B+C+D' data, a combined dataset 'A+B+C+D' was not produced.

For the H92 α line observations, the phase calibrator was J0118-216 and the bandpass calibrator was J2253+161. A spectral mode with 31 channels was used. The continuum images were obtained by averaging the data in the central 75% of the total band. The continuum data were processed using standard calibration and self-calibration procedures. The calibration and self-calibration used for the continuum data were then applied to the line data. All the images were made in the AIPS environment. The line images were Hanning-smoothed to reduce the Gibbs effect and the velocity resolution is 56.4 km s^{-1} . Further observational details are summarized by Mohan, Anantharamaiah, & Goss (2002) and Mohan, Goss, & Anantharamaiah (2005).

3. RESULTS

Figure 1 shows the radio continuum emission of NGC 253 at 43 GHz with an angular resolution of $1''.5 \times 1''.0$, P.A. = 0° ($1'' \simeq 12 \text{ pc}$). The integrated 43 GHz continuum flux density is $360 \pm 20 \text{ mJy}$, obtained by integrating the flux density over the nuclear $30''$ region using the task IRING in AIPS. The radio continuum image at 43 GHz shows two radio

continuum components, NE and SW, in addition to extended emission (see Figure 1). The continuum peak position of the NE component, $\alpha(\text{J2000}) = 00^h47^m33^s.17 \pm 0^s.01$, $\delta(\text{J2000}) = -25^\circ17'17''.4 \pm 0''.1$, coincides within $0''.2$ with the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997).

Figure 2 shows the H53 α velocity-channel images of NGC 253 with an angular resolution of $1''.5 \times 1''.0$ (P.A. = 0°). The H53 α line emission is detected toward both the NE and SW continuum components above a 3σ level (~ 2 mJy). The ionized gas is observed in the H53 α line at heliocentric velocities that range from 17 to 345 km s $^{-1}$. The velocity-integrated H53 α line emission (moment 0) is shown in Figure 3 superposed on the moment 0 of the H92 α line. There is good correspondence between the integrated line emission of the RRLs H53 α and H92 α . In addition, the peak position of the integrated H53 α line emission is in agreement with the peak position of the 43 GHz radio continuum image. In the H53 α line images, both the NE and SW components are spatially resolved only along the major axis.

Figure 4 shows the H53 α line spectrum integrated over the central $10''$ region of NGC 253. By fitting a Gaussian, the estimated central heliocentric velocity is 210 ± 10 km s $^{-1}$, the FWHM of the line is 230 ± 20 km s $^{-1}$ and the peak line flux density is 21 ± 2 mJy. The resulting fit is shown in Figure 4 along with the residuals to the fit. The central velocity is in agreement with previous estimates in the optical (225 ± 5 km s $^{-1}$; Arnaboldi et al. 1995) and IR (230 ± 10 km s $^{-1}$; Prada, Gutiérrez & McKeith 1998). The velocity integrated H53 α line flux density determined from our observations is $0.69 \pm 0.09 \times 10^{-20}$ W m $^{-2}$, in agreement with the previous measurement of $0.94 \pm 0.38 \times 10^{-20}$ W m $^{-2}$ derived from single-dish observations (Puxley et al. 1997). A Gaussian function was also used to determine the characteristics of the spectra obtained by integrating over the NE and SW regions. Table 2 lists the results for the total integrated H53 α line emission profile, as well as for profiles that correspond to the NE and SW components. The values listed for the H53 α line are peak flux density S_L , FWHM, the heliocentric velocity V_{Hel} and the velocity integrated H53 α line emission.

Figure 5 shows the velocity field (moment 1) of the H53 α line at an angular resolution of $1''.5 \times 1''.0$ (P.A. = 0°). Figure 6 shows the H92 α velocity field made using the 'B+C+D' data of Anantharamaiah & Goss (1996) at the same angular resolution. The velocity field of the ionized gas as observed in the H53 α line agrees with observations of the RRL H92 α (see section 4.2 for a detailed comparison). In the NE component of NGC 253 the red-shifted gas is observed toward the NW and the blue-shifted gas toward the SE. In the region located S of the radio continuum peak, there is a blue-shifted component that is more apparent in the H53 α line than in the H92 α line. A detailed comparison between the line profiles of the H53 α and H92 α in this region shows that the H53 α line is broader than the H92 α line by

$\sim 50 \text{ km s}^{-1}$ and there is a relative velocity shift between these two RRLs of $\sim 30 \text{ km s}^{-1}$. In the elongated SW component, the red-shifted gas is located at the SW and the blue-shifted gas is at the NE. The velocity gradient was measured, at $1''.5 \times 1''.0$ angular resolution, along the major (P.A. = 52°) and nearly along the minor (P.A. = -45°) axis for both RRLs the H53 α and H92 α . The H53 α velocity gradient along the major axis of NGC 253 (measured over the NE component) is $12 \pm 3 \text{ km s}^{-1} \text{ arcsec}^{-1}$, comparable to the corresponding H92 α velocity gradient ($\sim 11 \text{ km s}^{-1} \text{ arcsec}^{-1}$). The velocity gradients measured in the RRLs H53 α and H92 α (both at $1''.5 \times 1''.0$) along the P.A. = -45° are $42 \pm 8 \text{ km s}^{-1} \text{ arcsec}^{-1}$ and $24 \pm 2 \text{ km s}^{-1} \text{ arcsec}^{-1}$, respectively.

Figure 7 shows the H92 α velocity field at an angular resolution of $0''.36 \times 0''.21$ (P.A. = -3°). At this angular resolution, the H92 α line emission is detected only toward the NE component with an angular size of $\sim 0''.6$ (7 pc). Based on these H92 α data, a larger velocity gradient of $110 \pm 20 \text{ km s}^{-1} \text{ arcsec}^{-1}$ is measured along a P.A. $\simeq -45^\circ$. This velocity gradient is about a factor of four larger than the velocity gradient estimated using the lower angular resolution H92 α observations ($1''.5 \times 1''.0$). The lower velocity gradient measured in the low angular resolution image of H92 α ($1''.5 \times 1''.0$) is due to a beam dilution effect. By convolving the high angular resolution data of the H92 α with a Gaussian beam of $1''.5 \times 1''.0$ angular resolution, the velocity gradient measured along the P.A. = -45° is consistent with the lower angular resolution H92 α data.

4. DISCUSSION

4.1. Models for the radio continuum and recombination line emission

In Table 3, we summarize the 43 GHz continuum flux density measurement along with previous measurements (5 – 300 GHz) for the central $30''$ region of NGC 253. These flux density values have been used to determine the relative contributions from free-free, synchrotron and dust emission. At frequencies $< 50 \text{ GHz}$, the relative contributions of free-free and non-thermal emission are dominant compared to the thermal dust emission. However, at frequencies $> 50 \text{ GHz}$, the dust contribution is more significant. The estimated contribution of the thermal free-free emission at 43 GHz is $\sim 140 \text{ mJy}$, while the non-thermal emission accounts for $\sim 220 \text{ mJy}$. These values were obtained assuming that the thermal continuum free-free flux density shows $S_{\text{free-free}}(\nu) \propto \nu^{-0.1}$. Using the observed flux density measurements of the radio continuum in the range of 5 – 98 GHz, and following the procedure used by Turner & Ho (1983), the spectral index for the non-thermal emission is $\alpha_{\text{synchrotron}} = -0.73 \pm 0.06$. After subtracting the free-free and non-thermal emission from the total continuum emission over the 5 – 300 GHz frequency range, we obtain the spectral

index value for the dust emission $\alpha_{dust} = 3.9 \pm 0.2$. Figure 8 shows the contribution from thermal free-free, synchrotron and thermal dust emission along with the total radio continuum over the frequency range 5 to 300 GHz. The thermal free-free radio continuum flux density at 43 GHz may be used to estimate the ionization rate ($N_{Ly\alpha}$) from NGC 253 using (Schraml & Mezger 1969; Rodríguez et al. 1980),

$$\frac{N_{Ly\alpha}}{s^{-1}} = 9.0 \times 10^{43} \left(\frac{S_{C-th}}{mJy} \right) \left(\frac{T_e}{10^4 K} \right)^{0.35} \left(\frac{\nu}{4.9 GHz} \right)^{0.1} \left(\frac{D}{kpc} \right)^2, \quad (1)$$

where T_e is the electron temperature, ν is the frequency and D is the distance to NGC 253. The estimated ionizing flux at 43 GHz, assuming $T_e = 10^4$ K and $D = 2.5$ Mpc is $\sim 7 \times 10^{52} s^{-1}$. This $N_{Ly\alpha}$ value is a factor of ~ 5 lower than that estimated by Puxley et al. (1997), using the H40 α line flux density and assuming local thermodynamical equilibrium (LTE). However, the RRL H40 α line emission mainly arises from stimulated emission, implying a smaller value of the SFR. On the other hand, the star formation rate (Ψ_{OB}) can also be estimated using the relation $N_{Ly\alpha} = 5.4 \times 10^{52} \times \Psi_{OB} s^{-1}$ (Anantharamaiah et al. 2000), obtained assuming a mass range of $1 - 100 M_\odot$ in the Miller-Scalo initial mass function (IMF). The total SFR derived in the nuclear regions of NGC 253 is thus $\sim 1.3 M_\odot yr^{-1}$.

The emission in the RRLs H53 α and H92 α as well as the radio continuum at 43 and 8.3 GHz were modeled for the two continuum components (NE and the SW) of NGC 253 observed at an angular resolution of $1''.5 \times 1''.0$ (P.A. = 0°). The line and continuum flux densities were measured over regions where both the H92 α and H53 α are detected. The models consist of a collection of two families of HII regions, each with different electron densities. The electron density ranges that were explored are $n_e = 10^2 - 10^4 cm^{-3}$ and $n_e = 10^4 - 10^7 cm^{-3}$, for the low- and high-density gas components, respectively. The contribution from non-thermal synchrotron emission that arise from SNR and the possible AGN and free-free emission from HII regions were also considered. The RRL emission has been computed considering that the population of the atomic levels deviates from local thermodynamic equilibrium (LTE). The non-LTE effects result in both internally and externally stimulated line emission. The formalism used to compute the RRL and radio continuum flux densities at each frequency follows that used by Rodríguez-Rico et al. (2004). In these models, the electron density (n_e), temperature (T_e), size (s_o) and the number of HII regions (N_{HII}) are free parameters. In order to reduce the number of free parameters, the size of each HII region has been assumed to be a function of the electron density and the number of ionizing photons emitted by the embedded O star by $[s_o n_e^{2/3}] = U$, where U is a function of the spectral type of the star (Panagia 1973). In these models, early-type O7 stars have been used as the source of the ionizing continuum flux for each HII region. The results obtained for n_e and N_{HII} were constrained by the observed line and continuum flux densities as well

as the volume of the total line emission, assuming spherical HII regions.

The models suggest that the thermally ionized gas in the NE component consists of a collection of extended ($\sim 1 - 4$ pc) low-density ($\sim 10^2 - 10^3 \text{ cm}^{-3}$) HII regions and compact ($\sim 0.01 - 0.06$ pc) high-density ($\sim 10^5 - 10^6 \text{ cm}^{-3}$) HII regions. In order to reproduce the observations, the mass of ionized gas in the low-density component must be a factor of $\sim 10^3$ larger than the mass of ionized gas in the high-density component. The ionized gas in the SW region also consists of low- and high-density HII regions, characterized by $n_e \simeq 10^2 \text{ cm}^{-3}$ and $n_e \simeq 10^5 - 10^6 \text{ cm}^{-3}$. Table 4 lists the physical parameters of these HII regions: the electron temperature (T_e), electron density (n_e), size, emission measure (EM), mass of ionized gas, continuum optical depth (τ_c) at 8.3 and 43 GHz, departure coefficients (b_n and $\beta_n = 1 - (kT_e/h\nu_L)d \ln b_n/dn$, where n is the quantum number) for the H53 α and H92 α RRLs, the contribution of free-free emission and the Lyman continuum photons rate. The second and third columns list these parameters for the low and high-density HII regions on the NE component. The fourth and fifth columns list the corresponding parameters for the SW component. Based on these models, the RRL H92 α arises mainly as externally stimulated line emission from the extended low-density ($\sim 10^3 \text{ cm}^{-3}$) HII regions, with $\beta_n < -20$.

The thermal free-free contribution from both the low- and high-density component to the total observed continuum emission ranges from $\sim 30\%$ to $\sim 80\%$. The total mass of thermally ionized gas in each component (NE and the SW) is $\sim 10^3 M_\odot$. The Lyman continuum emission rate of $5.9 \times 10^{52} \text{ s}^{-1}$ obtained from the RRL emission models (see Table 4) is consistent with $7 \times 10^{52} \text{ s}^{-1}$, obtained from the continuum emission models (shown in Figure 8). The Lyman continuum emission rates for the NE and SW components (listed in Table 4) were obtained only for regions where H53 α line emission was detected. On the other hand, the value of $7 \times 10^{52} \text{ s}^{-1}$ was estimated by integrating over the central $30''$ region, which explains the slightly different results. The results obtained for the low-density gas component for the NE component of NGC 253 are in agreement with the results obtained by Mohan, Goss, & Anantharamaiah (2005) for the 15 pc region, observed with higher angular resolution observations ($\sim 0''.3$) and using VLA H166 α , H92 α and H75 α line data. Even though the mass contribution of the high density HII regions is only $\sim 1\%$ of the total HII mass, this feature contributes $\sim 40\%$ of the total H53 α line emission.

As noted before by Mohan, Goss, & Anantharamaiah (2005), high angular resolution observations are essential in the determination of the physical parameters of both low and high-density HII regions. In addition to high angular resolution, high frequency observations (e.g. H53 α) are required to determine the properties of the high-density ($\sim 10^5 \text{ cm}^{-3}$) HII regions. Non-LTE effects are important, leading to an enhancement of the line emission by a

factor of ~ 2 . Thus, the results obtained assuming LTE conditions overestimate the number of HII regions (and also the SFR) that must exist in NGC 253.

4.2. Kinematics

The previous H92 α line observations at $1''.8 \times 1''.0$ angular resolution (Anantharamaiah & Goss 1996) revealed velocity gradients of $\sim 11 \text{ km s}^{-1} \text{ arcsec}^{-1}$ and $\sim 18 \text{ km s}^{-1} \text{ arcsec}^{-1}$ along the major axis and minor axis, respectively. A qualitative comparison of the velocity field observed in the H53 α line and the previously reported H92 α line velocity field reveals kinematical behaviors that are consistent, i.e. the regions with red-shifted and blue-shifted ionized gas coincide (see Figs. 5 and 6). The coincidence of the red- and blue-shifted regions in the H53 α and H92 α velocity fields implies that both the low- and high-density ionized gas components rotate in the same sense.

In order to compare in detail the kinematics of the ionized gas as observed in the H53 α and the H92 α lines, we constructed PV diagrams along the major axis (P.A. = 52°) using the task SLICE in GIPSY. These PV diagrams are shown in Figure 9; the white line is the resulting fit to the velocity gradient of $11 \text{ km s}^{-1} \text{ arcsec}^{-1}$. The same procedure was used to obtain PV diagrams along the P.A. = -45° , shown in Figure 10; the white lines are the resulting fits to the H92 α velocity gradient ($24 \text{ km s}^{-1} \text{ arcsec}^{-1}$) and the H53 α velocity gradient ($42 \text{ km s}^{-1} \text{ arcsec}^{-1}$). In Figure 10 we also show the H92 α and H53 α spectra superimposed at different offset positions from the central source (5.79-39.0); these spectra were normalized based on the peak line flux densities. By inspection of the different spectra obtained at the negative offset positions (between $-0''.6$ and $-0''.9$ in Figure 10), a relative velocity shift ($\sim 30 \pm 5 \text{ km s}^{-1}$) is observed between the peak flux density of the H53 α and the H92 α lines. Based on the line emission models, these two RRLs trace different density components (see section 4.1). The small velocity shift between these two RRLs on the NE component suggests that each density component has slightly different kinematics.

4.2.1. Gaseous bar structure, outflow or an accreted object

Observations at IR wavelengths have revealed the existence of a gaseous bar in NGC 253 (Scoville et al. 1985). In a bar potential the gas follows two types of orbits, x1 and x2. The x1 (bar) orbits are those extended along the major axis of the bar and the x2 (anti-bar) orbits are those oriented perpendicular to the bar major axis. In the case of NGC 253, the x1 and x2 orbits would be oriented on the plane of the sky at P.A. of $\sim 70^\circ$ and $\sim 45^\circ$, respectively.

In the H53 α and H92 α RRL images (at $1''.5 \times 1''.0$ angular resolution) the orientation of the largest velocity gradient is nearly perpendicular to the orientation of the x2 orbits. Since the ionized gas on the NE component rotates in an opposite sense compared to the CO (Anantharamaiah & Goss 1996; Das, Anantharamaiah & Yun 2001), a simple bar potential does not account for the differences observed between the velocity fields of the RRLs (H92 α and H53 α) and CO. A secondary bar inside the primary bar may be invoked to explain the kinematics observed in the center of NGC 253. However, further observations and modeling are required to investigate the existence of this secondary bar.

Weaver et al. (2002) proposed the presence of a starburst-driven nuclear outflow collimated by a dusty torus, based on X-ray observations of NGC 253. In this model, the thermally ionized gas in the center of NGC 253 should be distributed in both a starburst ring and a starburst-driven outflow (Weaver et al. 2002). Observations of the RRL H92 α toward the starburst galaxy M82 (Rodríguez-Rico et al. 2004), have proven that RRLs may be used to study the ionized gas associated with galactic outflows. The largest velocity gradient observed in the RRL H92 α is oriented nearly along the minor axis of NGC 253 (P.A. = -45°). Based on this orientation and assuming the H92 α RRL in the NE component traces the ionized gas in the outflow, the receding side of this outflow would be on the NW and the approaching side on the SE. If this is the case all the observed ionized gas would be tracing the outflow, explaining the different rotation sense between the CO and the ionized gas. However, it seems unlikely that all the ionized gas is associated with the outflow.

Das, Anantharamaiah & Yun (2001) propose that the kinematics of the ionized gas traced by the H92 α RRL can be explained if there is an accreted object with mass of $\sim 10^6 M_\odot$. The CO gas which traces the galactic disk of NGC 253 is moving in an opposite sense compared to the ionized gas that may be associated with the compact object. Based on the H53 α velocity gradient ($\sim 42 \text{ km s}^{-1} \text{ arcsec}^{-1}$) along the minor axis of the NE component ($\sim 30 \text{ pc}$), the inferred dynamical mass is $\sim 5 \times 10^6 M_\odot$. This mass estimate is consistent with that of the accreted object proposed by Das, Anantharamaiah & Yun (2001). The existence of a compact object is further supported by the higher angular resolution ($0''.36 \times 0''.21$) H92 α observations (Figure 7), revealing a larger velocity gradient ($\sim 110 \text{ km s}^{-1} \text{ arcsec}^{-1}$, at P.A. $\simeq -45^\circ$) over the central $\sim 0''.6$ (7 pc). This H92 α velocity gradient of $\sim 110 \text{ km s}^{-1} \text{ arcsec}^{-1}$ implies a dynamical mass of $\sim 7 \times 10^6 M_\odot$, similar to the mass determined from the $1''.5 \times 1''.0$ angular resolution observations of the RRLs H53 α and H92 α . The $\sim 7 \times 10^6 M_\odot$ dynamical mass is based on observations over a region a factor of three times smaller than that observed in the $1''.5 \times 1''.0$ angular resolution images.

The estimated dynamical mass ($\sim 7 \times 10^6 M_\odot$) for the nuclear region of NGC 253 is comparable to that of the compact source at the nucleus of our galaxy ($\sim 4 \times 10^6 M_\odot$, Ghez

et al. 2005). This mass estimate of $\sim 7 \times 10^6 M_{\odot}$ for the central region of NGC 253 could exist in the form of a large number of stars combined with ionized gas and may also contain an AGN. If the Lyman continuum photons rate ($\sim 7 \times 10^{52} \text{ s}^{-1}$) is mainly due to O5 stars, each emitting $\sim 5 \times 10^{48} \text{ s}^{-1}$, then there must be $\sim 10^4$ O5 stars in the NE component. Using Salpeter’s initial mass function and a mass range of $0.1 - 100 M_{\odot}$, the total mass in stars in the NE component is $\sim 10^7 M_{\odot}$. The ionized gas could be gravitationally bounded by the stars and consequently the black hole mass would be $\leq 10^7 M_{\odot}$. The existence of an AGN has been proposed from radio continuum observations (Turner & Ho 1985; Ulvestad & Antonucci 1997) and RRL H92 α observations (Mohan, Anantharamaiah, & Goss 2002). Radio continuum observations (1.3 to 20 cm), reveal that the strongest radio source 5.79-39.0 has a brightness temperature $> 40,000 \text{ K}$ at 22 GHz and is unresolved ($< 1 \text{ pc}$, Ulvestad and Antonucci 1997). Broad ($> 100 \text{ km s}^{-1}$) H₂O maser line emission is observed toward the nuclear regions supporting the existence of a massive object in the center of NGC 253 (Nakai et al. 1995).

In order to account for the different kinematics observed for the ionized and the molecular gas, two possible scenarios can be proposed: (1) a dense object that is accreted into the nuclear region of NGC 253, (2) the ionized gas is moving in a starburst-driven outflow and/or (3) a secondary bar exists within the primary bar, as proposed for other galaxies (Friedli & Marinet 1993). The accreted object model is supported by the high angular resolution H92 α observations; the estimated dynamical mass of $\sim 7 \times 10^6 M_{\odot}$ is concentrated in a $\leq 7 \text{ pc}$ region and the ionized gas traced by the RRLs moves in the opposite direction compared to the larger scale CO. In the RRLs H53 α and H92 α , we find no evidence that confirms the existence of a secondary bar. An S-shape in the velocity field is characteristic of a bar (Anantharamaiah & Goss 1996). Thus, for a secondary bar a second S-shaped pattern would be observed in the velocity field which is not appreciated in the H92 α velocity structure (see Figure 7). However, this scenario cannot be ruled out and higher angular and spectral resolution observations are necessary to discern between these three models.

5. CONCLUSIONS.

The H53 α RRL and radio continuum at 43 GHz were observed at high angular resolution ($1''.5 \times 1''.0$) towards NGC 253. We have also reanalyzed previous observations of the RRL H92 α made at an angular resolutions of $1''.5 \times 1''.0$ (Anantharamaiah & Goss 1996) and $0''.36 \times 0''.21$ (Mohan, Anantharamaiah, & Goss 2002).

Based on the 43 GHz radio continuum flux density and previous measurements at lower and higher frequencies, we have estimated the contribution from free-free emission

(~ 100 mJy at 43 GHz). Using this value for the free-free emission, the derived SFR in the nuclear region of NGC 253 $\sim 1.3 M_{\odot} \text{ yr}^{-1}$. The RRLs (H53 α and H92 α) and radio continuum (at 43 and 8.3 GHz) emission have been modeled using a collection of HII regions. Based on the models, the RRL H53 α enables us to trace the compact (~ 0.1 pc) high-density ($\sim 10^5 - 10^6 \text{ cm}^{-3}$) HII regions in NGC 253. The total mass of high-density ionized gas in the central 18 pc is $\sim 10^3 M_{\odot}$. A large velocity gradient ($\sim 42 \text{ km s}^{-1} \text{ arcsec}^{-1}$, P.A. $\sim -45^\circ$) is observed in the H53 α line. The orientation and amplitude of the velocity gradients (angular resolution $\sim 1''.2$) derived using the H53 α and H92 α lines agree. The high angular resolution observations ($0''.36 \times 0''.21$) of the H92 α line reveal a larger velocity gradient ($\sim 110 \text{ km s}^{-1} \text{ arcsec}^{-1}$); this large velocity gradient implies a dynamical mass on the NE component (≤ 7 pc) of $\sim 7 \times 10^6 M_{\odot}$, supporting the existence of an accreted compact object.

The orientation of the H53 α and H92 α velocity gradients does not agree with the CO kinematics. The different kinematics observed over a larger region of the disk of NGC 253 also suggests the existence of an accreted object. The derived dynamical mass ($\sim 7 \times 10^6 M_{\odot}$) can be accounted for by a large stellar density and/or the presence of an AGN. The star formation activity in NGC 253 may be the result of a merger process of NGC 253 and this proposed massive compact object.

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Table 1. Observing parameters for NGC 253 using the VLA.

Parameter	H53 α RRL (43 GHz)
Right ascension (J2000)	00 ^h 47 ^m 33 ^s .18
Declination (J2000)	−25°17′17″.0
Angular resolution continuum	1″.5 × 1″.0, P.A.= 0°
Angular resolution line	1″.5 × 1″.0, P.A.= 0°
On-source observing duration (hr)	8
Bandwidth (MHz)	125
Number of spectral channels	38
Center V_{Hel} (km s ^{−1})	200
Velocity coverage (km s ^{−1})	1000
Velocity resolution (km s ^{−1})	44
Amplitude calibrator	J0137 + 331
Phase calibrator	J0120 − 270
Bandpass calibrator	J0319 + 415
RMS line noise per channel (mJy/beam)	0.65
RMS, continuum (mJy/beam)	0.2

Table 2. H53 α and H92 α line parameters for NGC 253.

Feature	H53 α					H92 α				
	S_{C43}^a (mJy)	S_L (mJy)	ΔV_{FWHM} (km s $^{-1}$)	V_{Hel} (km s $^{-1}$)	$S_L \cdot \Delta V_{FWHM}$ ($\times 10^{-20}$ W m $^{-2}$)	$S_{C8.3}^a$ (mJy)	S_L (mJy)	ΔV (km s $^{-1}$)	V_{Hel} (km s $^{-1}$)	$S_L \cdot \Delta V_{FWHM}$ ($\times 10^{-22}$ W m $^{-2}$)
NGC 253 NE	134 ± 5	9.0 ± 0.5	200 ± 10	220 ± 5	0.25 ± 0.01	278 ± 10	4.5 ± 0.1	190 ± 5	200 ± 2	2.4 ± 0.2
NGC 253 SW	24 ± 2	2.8 ± 0.3	130 ± 20	215 ± 10	0.04 ± 0.01	40 ± 4	0.7 ± 0.1	160 ± 15	220 ± 10	0.3 ± 0.03
NGC 253 Total	360 ± 20	21 ± 2	230 ± 20	210 ± 10	0.69 ± 0.09	605 ± 10	9.0 ± 0.5	190 ± 10	206 ± 4	4.7 ± 0.5

^aContinuum emission was obtained by integrating over the region where both RRLs H53 α and H92 α were detected.

Table 3. Observed continuum flux densities for NGC 253^a.

Frequency (GHz)	Flux density (mJy)
5	1400 ± 70 ^b
8.3	1100 ± 25 ^c
15	640 ± 30 ^b
43	360 ± 20 ^d
85	350 ± 50 ^e
99	320 ± 30 ^f
230	1700 ± 200 ^g
300	4400 ± 1700 ^h

^aIntegrated flux density measured over the inner $\sim 30''$ region.

^bTurner & Ho (1983).

^cMohan et al. (2002).

^dThis work.

^eCarlstrom et al. (1990).

^fPeng et al. (1996).

^gKrugel et al. (1990).

^hChini et al. (1984).

Table 4. Results from models using a collection of HII regions for NGC 253.

Parameter	NE region		SW region	
	Low density ^a	High density ^a	Low density ^a	High density ^a
T_e (K)	7500 ± 2500	7500 ± 2500	5000 ± 1000	5000 ± 1000
n_e (cm ⁻³)	$1.6 \pm 1.4 \times 10^3$	$5.5 \pm 4.5 \times 10^5$	200 ± 100	$6.5 \pm 3.5 \times 10^5$
Size (pc)	2.4 ± 1.7	0.04 ± 0.03	4.5 ± 1.5	0.02 ± 0.01
EM (cm ⁻⁶ pc)	$3 \pm 2 \times 10^6$	$50 \pm 45 \times 10^8$	$1.5 \pm 1 \times 10^5$	$6 \pm 4 \times 10^9$
M_{HII} (M _⊙)	$3 \pm 2 \times 10^3$	7 ± 6	$5 \pm 3 \times 10^3$	0.4 ± 0.3
τ_C (8.3 GHz)	$6 \pm 5 \times 10^{-3}$	32 ± 30	$6 \pm 5 \times 10^{-4}$	60 ± 40
τ_C (43 GHz)	$6 \pm 5 \times 10^{-5}$	1.0 ± 0.9	$4 \pm 3 \times 10^{-5}$	1.9 ± 1.3
b_n (H92 α)	$0.881 - 0.973$	$0.997 - 0.999$	$0.819 - 0.887$	$0.998 - 0.999$
b_n (H53 α)	$0.70 - 0.79$	$0.96 - 0.98$	$0.64 - 0.65$	$0.97 - 0.98$
β_n (H92 α)	-55 ± 32	-1.25 ± 0.75	-70 ± 10	-0.15 ± 0.14
β_n (H53 α)	-27 ± 13	-10 ± 3	-13 ± 2	-5 ± 1
S_{ff-43}^b (mJy)	70 ± 30		19 ± 2	
N_{Lyc} ($\times 10^{52}$ s ⁻¹)	5 ± 2		0.9 ± 0.1	

^aBoth components were used to fit the continuum emission at 8.3 and 43 GHz as well as the flux densities in the RRLs H92 α and H53 α .

^bFree-free continuum flux density at 43 GHz obtained summing the contributions from the low and high-density components.

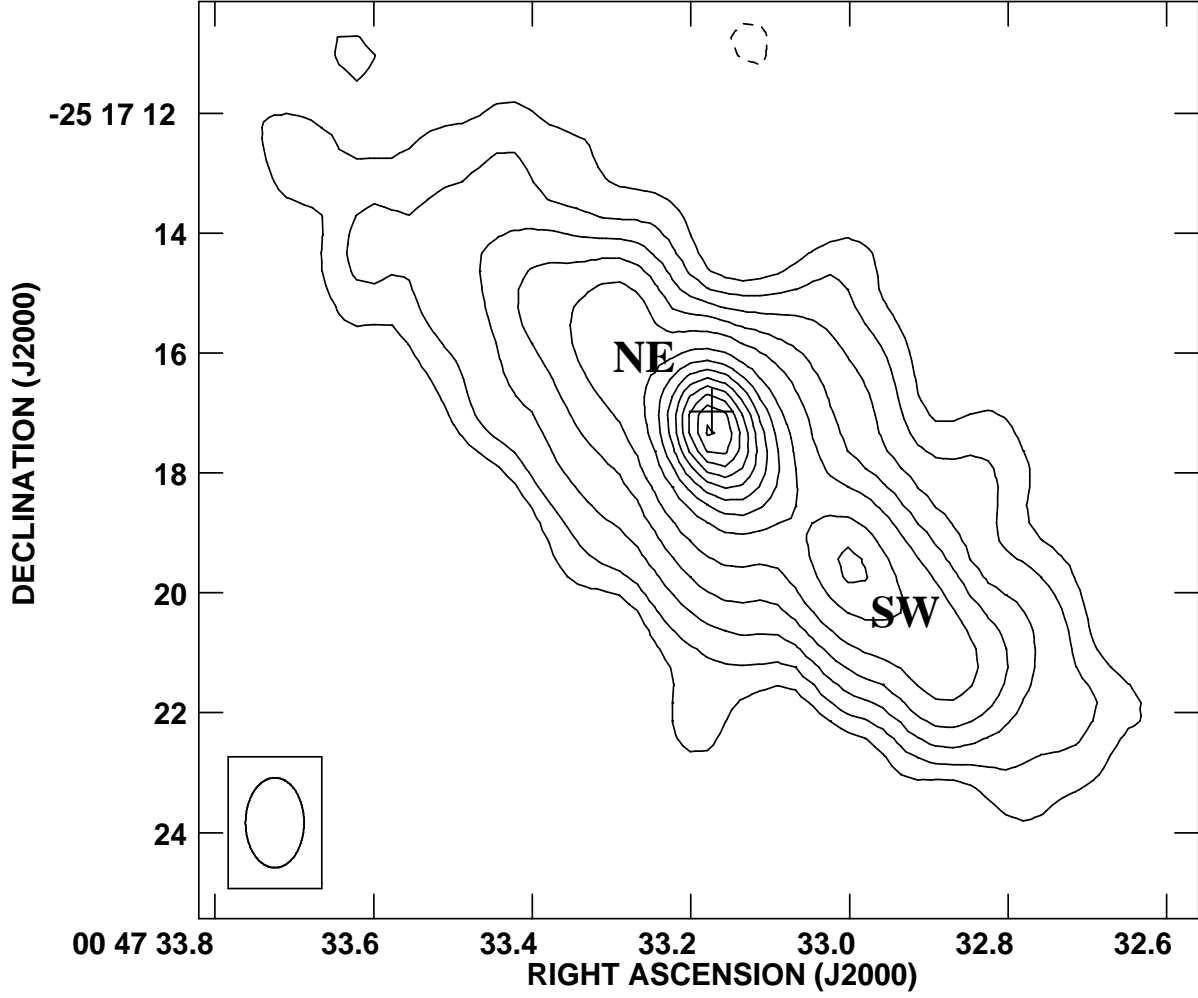


Fig. 1.— Radio continuum image of NGC 253 at 43 GHz obtained using the VLA. Contour levels are drawn at $-3, 3, 6, 12, 24, 48, 96, 144, 192, 240, 288, 336, 384,$ and 432 times the rms of $0.2 \text{ mJy beam}^{-1}$. The cross shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997). The angular resolution is $1''.5 \times 1''.0$, P.A.= 0° .

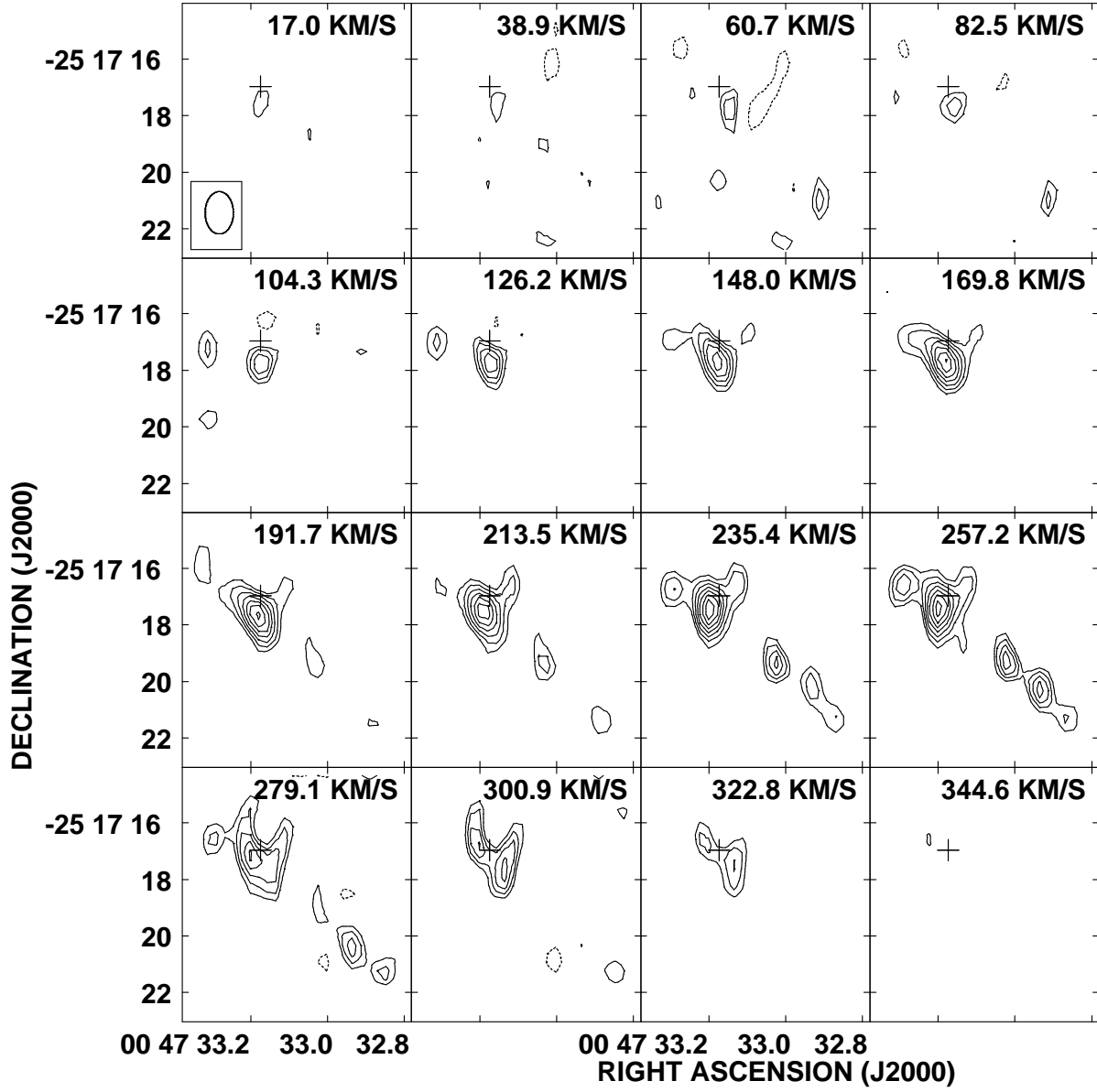


Fig. 2.— Channel images of the H53 α line emission toward NGC 253 obtained using the VLA. Contours are $-3, 3, 4, 5, 6, 7, 8, 9$ and 10 times $0.65 \text{ mJy beam}^{-1}$, the rms noise. The cross shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997). The synthesized beam ($1''.5 \times 1''.0$ FWHM, P.A. = 0°) is shown in the first panel. The central heliocentric velocity is given above for each image.

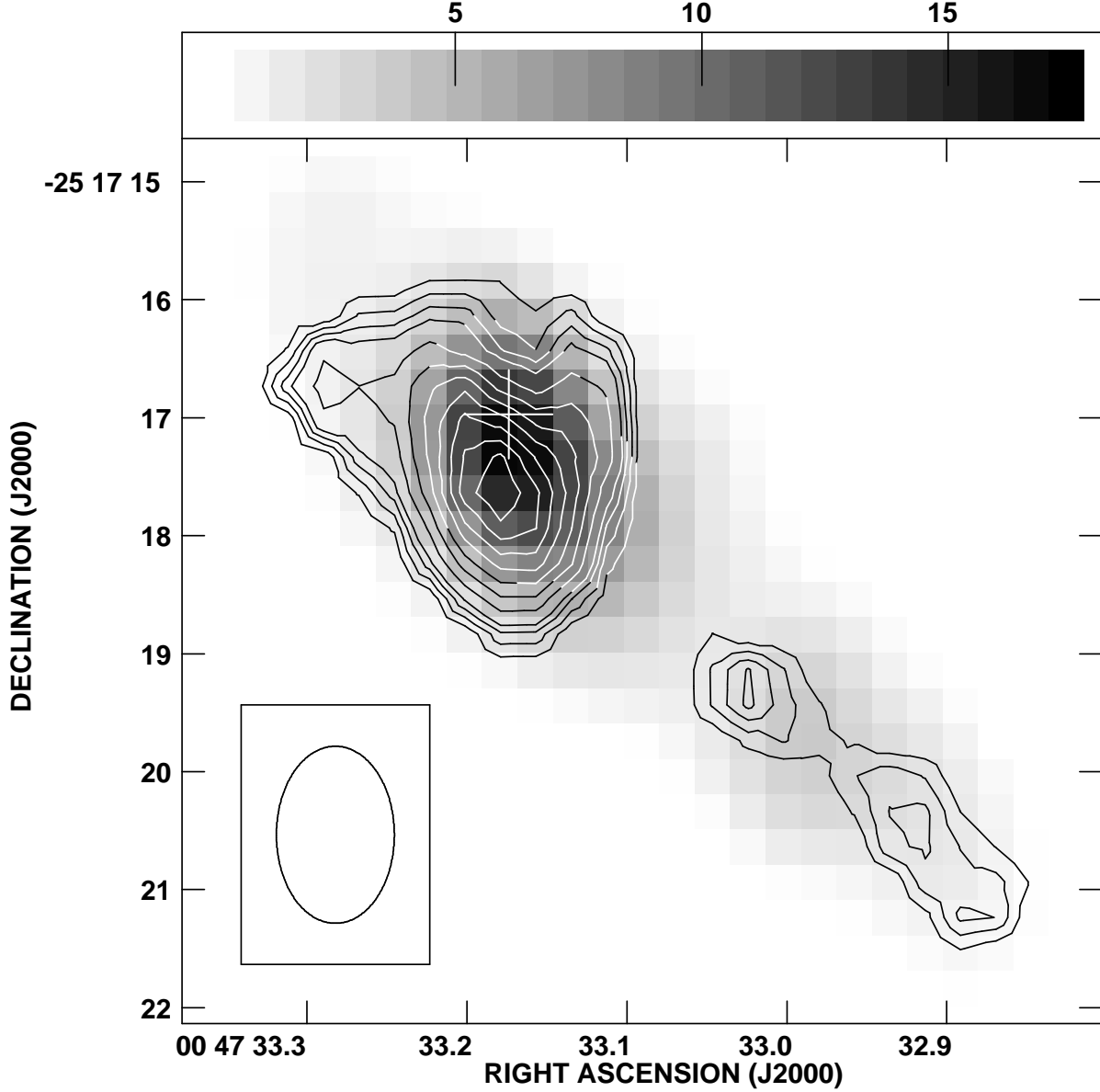


Fig. 3.— The velocity integrated (moment 0) of the H53 α line emission (contours) superposed on the moment 0 of the H92 α line emission (gray scale) toward NGC 253. Contour levels are drawn at 5, 10, 15, 20, 30, ..., 90% the peak line emission of 1.16 Jy beam⁻¹ km s⁻¹. The gray scale (moment 0 of H92 α) covers the range 0.18 – 18 Jy beam⁻¹ km s⁻¹. The cross (+) shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997). The HPFW, for both the H53 α and the H92 α line images is 1''.5 \times 1''.0, P.A.= 0°.

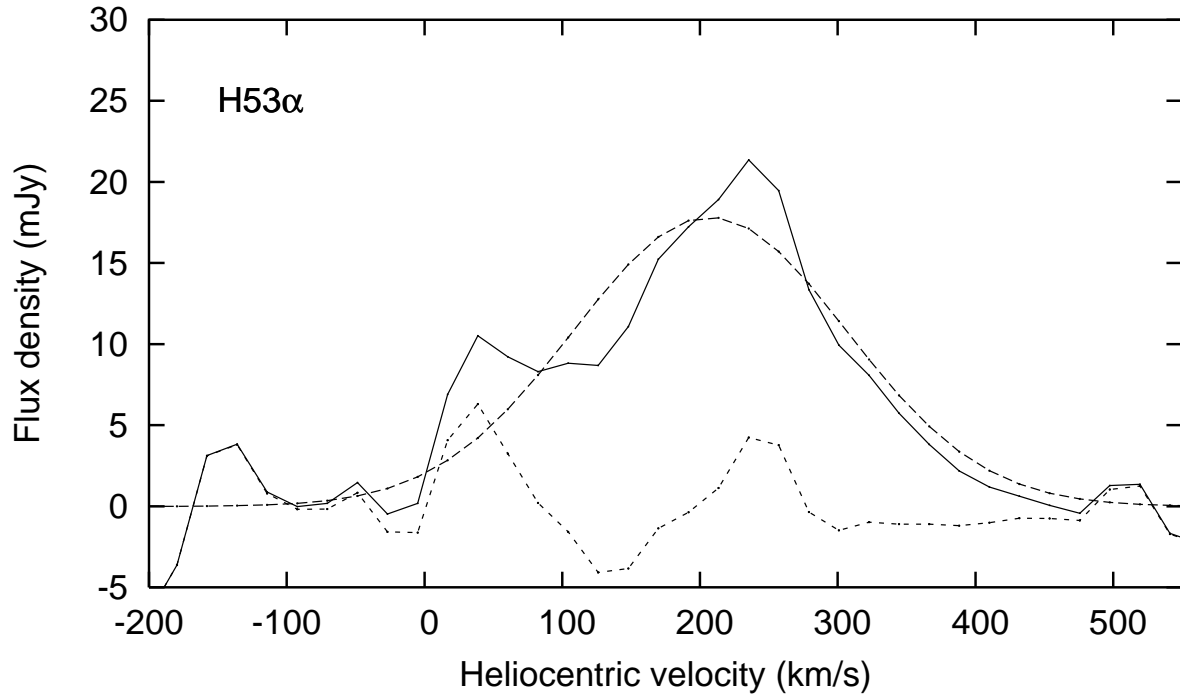


Fig. 4.— Total integrated H53 α spectrum from NGC 253, obtained by integrating over the central 10". The thick line shows the data, the dashed line shows the Gaussian fit and the dash-dotted line shows the residuals to this fit.

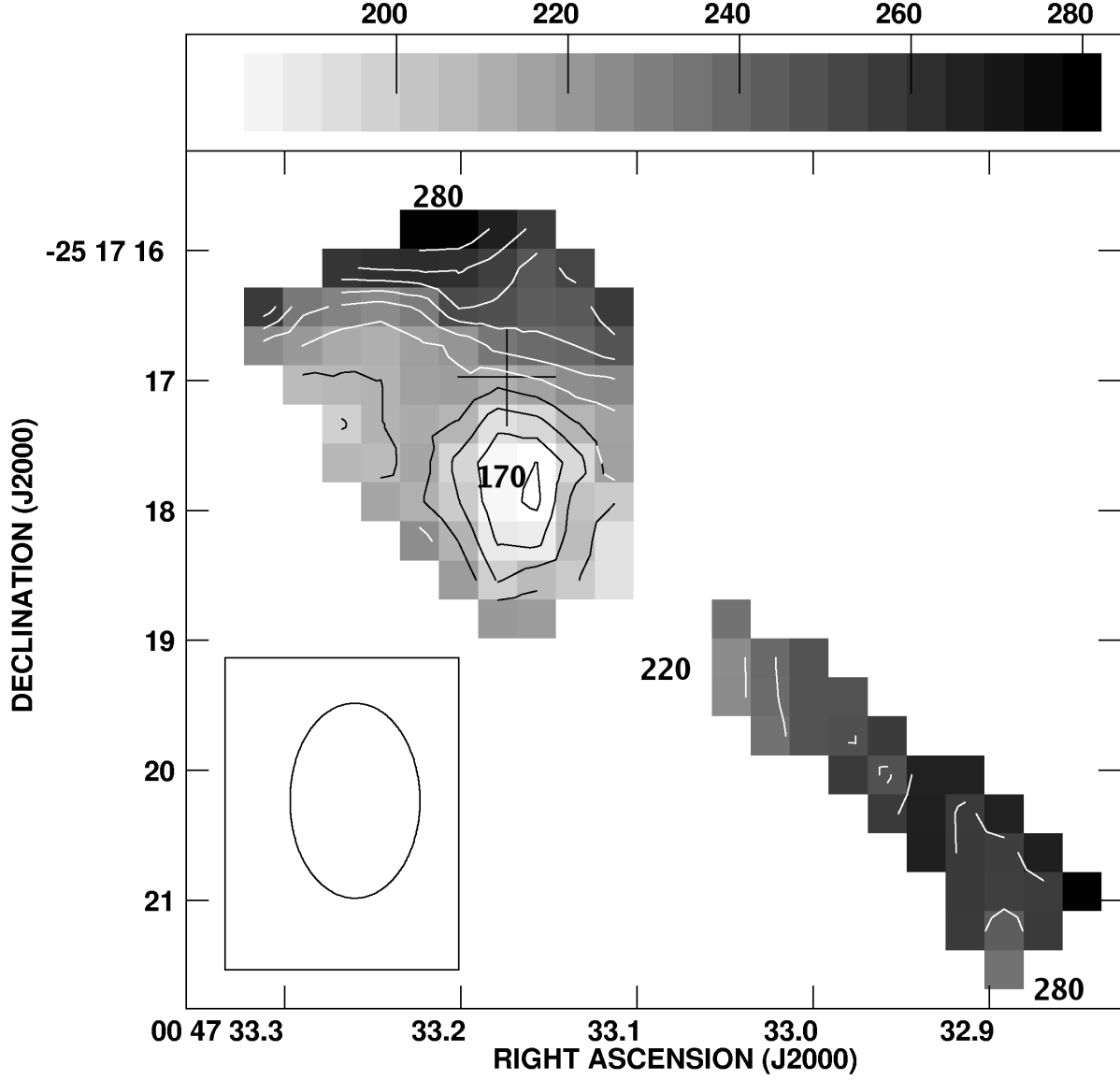


Fig. 5.— Velocity field observed in the H53 α line from NGC 253. Contour levels are the heliocentric velocities at 180, 190, 200, 210, 220, 230, 240, 250, 260, and 270 km s⁻¹. The gray scale ranges from 170 to 280 km s⁻¹. The cross (+) shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997). The HPFW is 1".5 \times 1".0, P.A.= 0°.

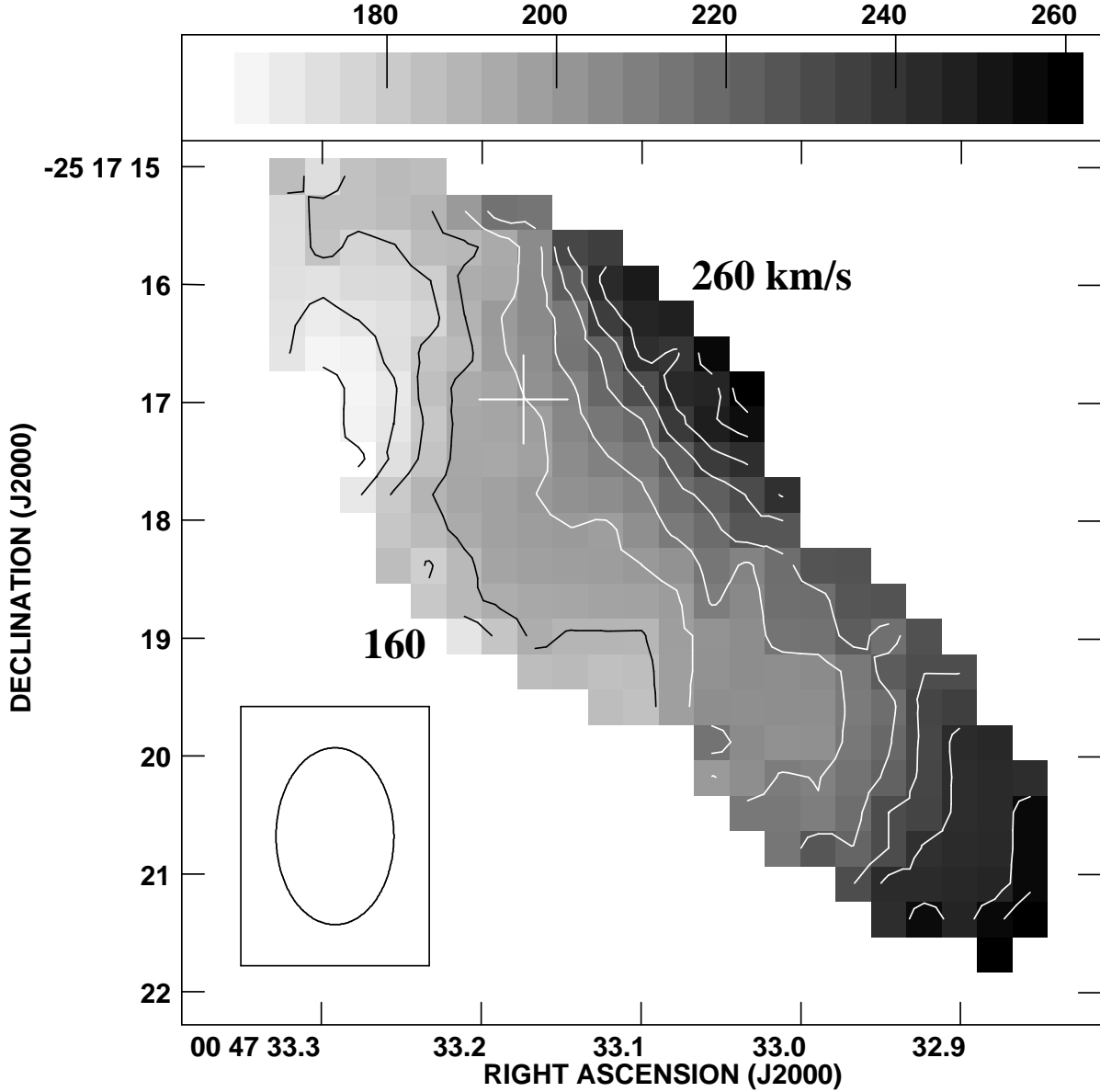


Fig. 6.— The H2 α velocity field of NGC 253 (Anantharamaiah & Goss 1996), is shown in contours superposed on the gray scale image of the same H2 α velocity field. Contour levels are drawn for the heliocentric velocities of the ionized gas from 160 to 260 km s $^{-1}$ in steps of 10 km s $^{-1}$ and the gray scale covers the same heliocentric velocity range. The cross (+) shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997). The HPFW is $1''.5 \times 1''.0$, P.A.= 0° .

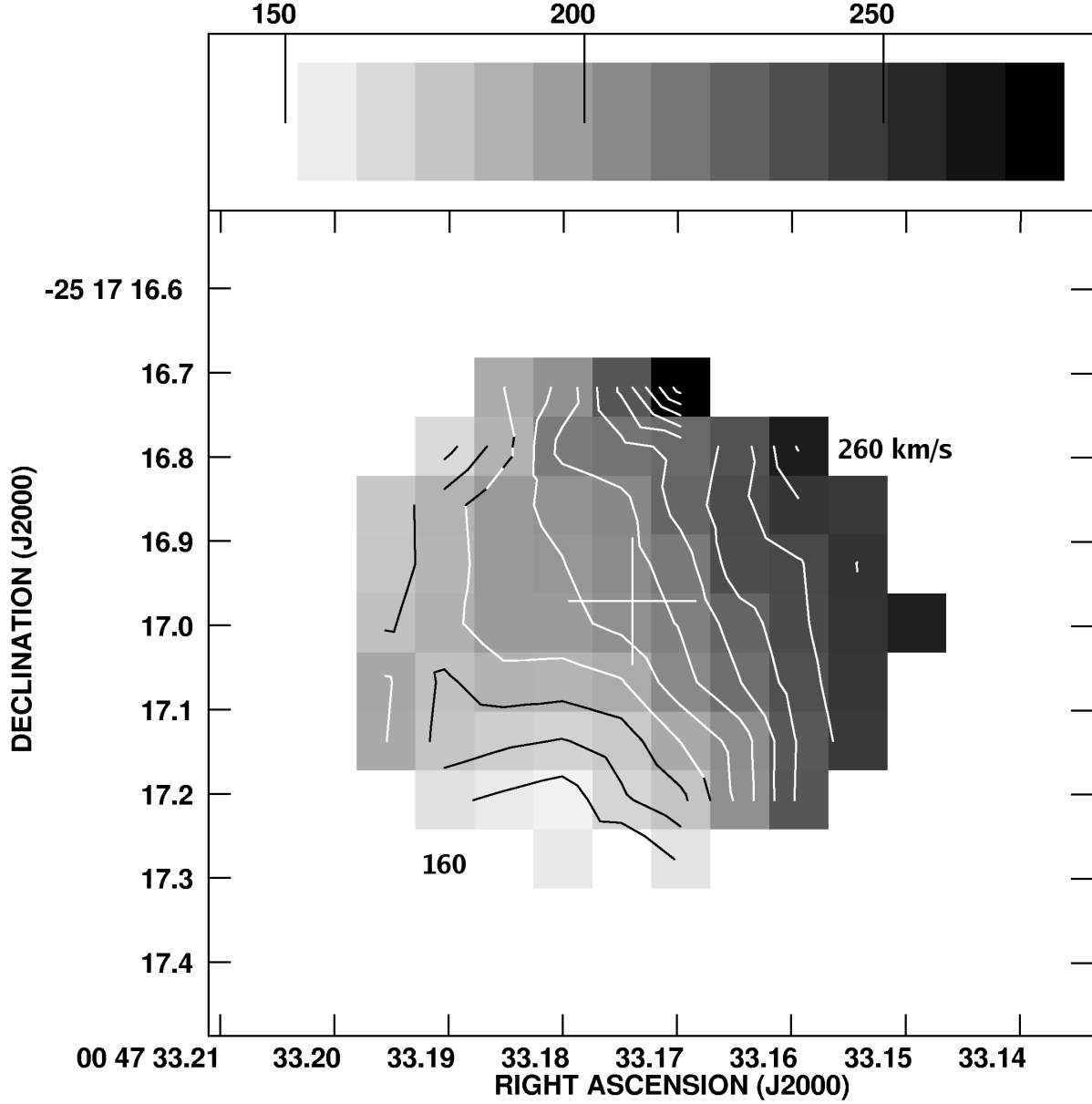


Fig. 7.— High angular resolution ($0''.36 \times 0''.21$, P.A. = -3°) heliocentric velocity field (moment 1) image of the H92 α line emission toward NGC 253 obtained using the VLA A array data. Contour levels are drawn at 160, 170, ..., 260 km s $^{-1}$. The cross (+) shows the position of the compact source 5.79-39.0 (Ulvestad & Antonucci 1997).

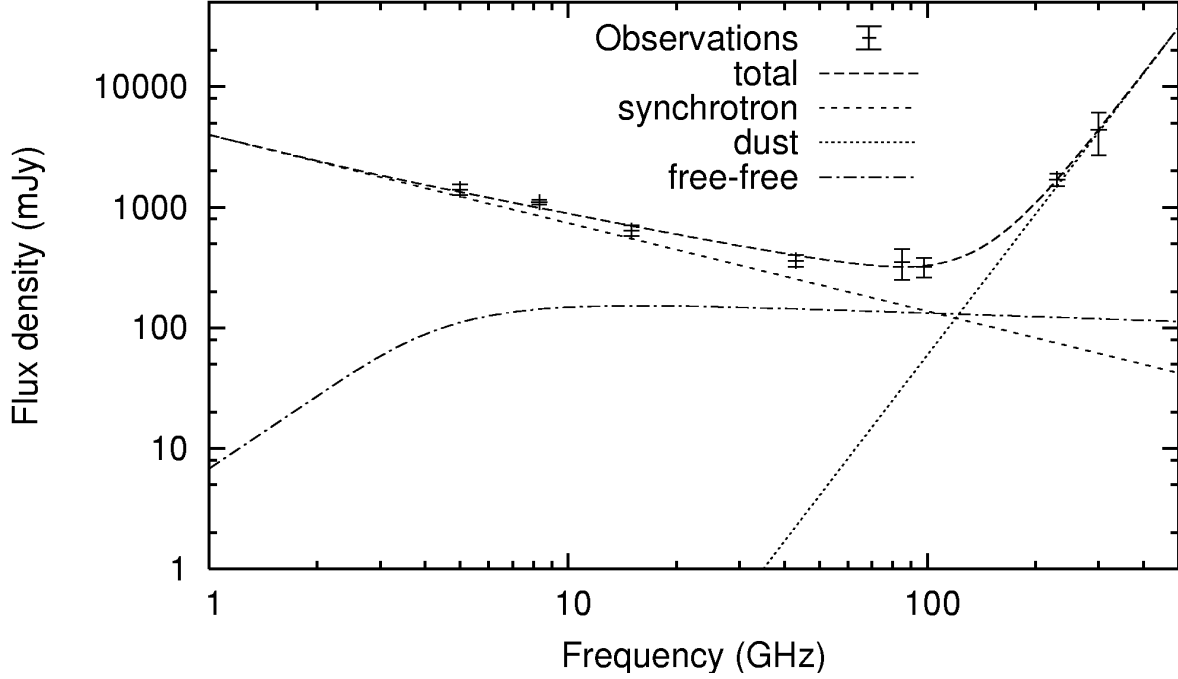


Fig. 8.— Integrated radio continuum emission measured toward the nuclear $30''$ region of NGC 253 at 5, 15 GHz (Turner & Ho 1983), 43 GHz (this work), 85 GHz (Carlstrom et al. 1990), 98 GHz (Peng et al. 1996), 230 GHz (Krugel et al. 1990) and 300 GHz (Chini et al. 1984). The contributions to the continuum flux density are: free-free ($S_{free-free} \propto \nu^{-0.1}$), synchrotron ($S_{synchrotron} \propto \nu^{-0.7}$) and dust ($S_{dust} \propto \nu^{3.9}$) emission which are shown as indicated.

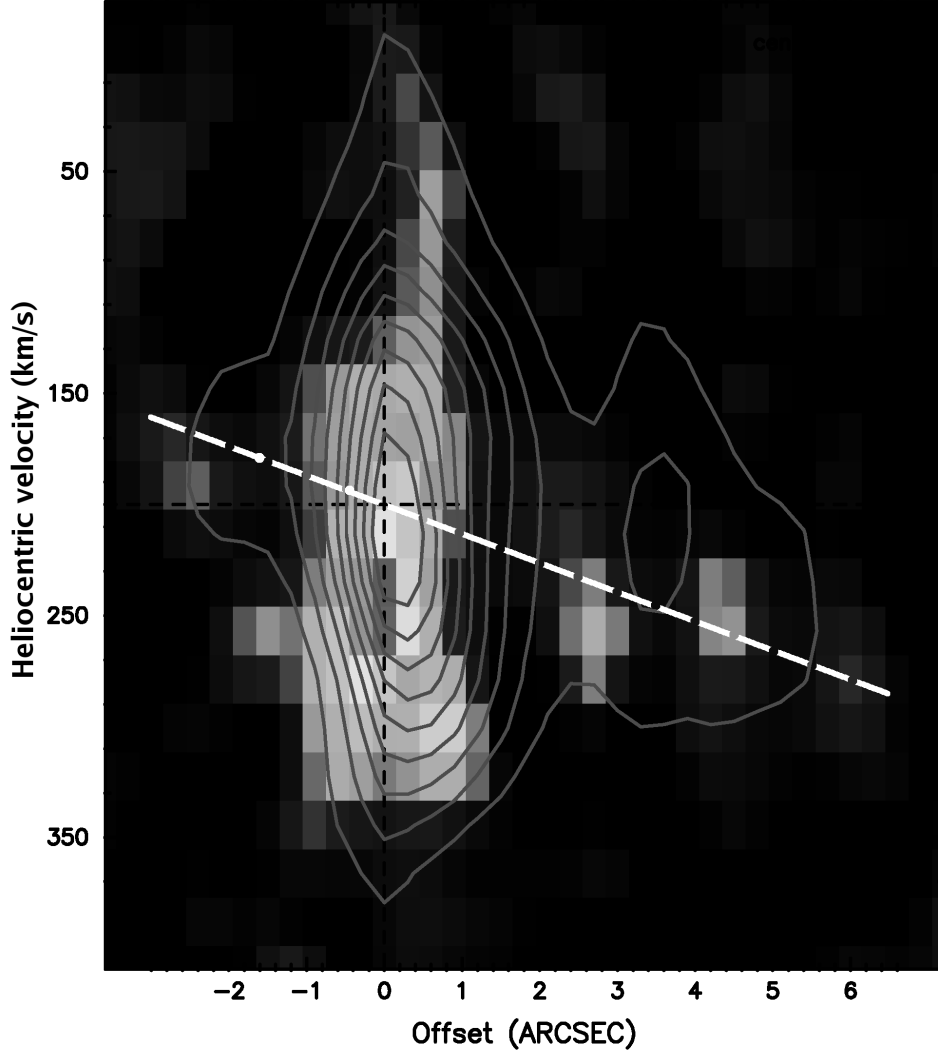


Fig. 9.— Position-velocity comparisons along the major axis (P.A.= 52°) of NGC 253. The H53 α RRL PV diagram (color scale) was constructed from the data with angular resolution of $1''.5 \times 1''.0$, P.A.= 0° and velocity resolution of 44 km s^{-1} . The color scale covers the range $0.64 - 6.4 \text{ mJy beam}^{-1}$. The H92 α RRL PV diagram (contours) was constructed from the data of Anantharamaiah & Goss (1996) with angular resolution of $1''.5 \times 1''.0$, P.A.= 0° and velocity resolution 56 km s^{-1} . Contours are 10%, 20%, ..., 90% of the peak intensity 3.9 mJy/beam . The white dashed line shows the fitted velocity gradient of $11 \text{ km s}^{-1} \text{ arcsec}^{-1}$.

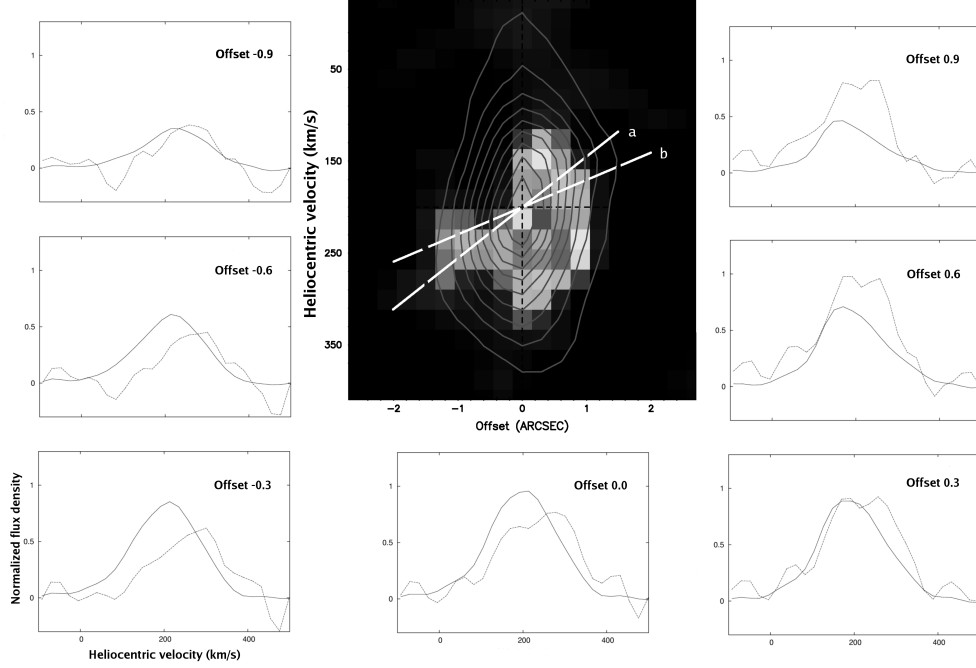


Fig. 10.— Position-velocity diagrams along a P.A. = -45° in NGC 253. The H53 α RRL PV diagram (color scale) was constructed from the data with angular resolution of $1''.5 \times 1''.0$, P.A. = 0° and velocity resolution of 44 km s^{-1} . The color scale is from 0.64 to 6.4 mJy/beam. The H92 α RRL PV diagram (contours) was constructed from the data of Anantharamaiah & Goss (1996), with angular resolution of $1''.5 \times 1''.0$, P.A. = 0° and velocity resolution of 56 km s^{-1} . Contours are 10%, 20%, ..., 90% of the peak intensity 3.9 mJy/beam. The white dashed lines marked with 'a' and 'b' show the fitted velocity gradients of $42 \text{ km s}^{-1} \text{ arcsec}^{-1}$ and $25 \text{ km s}^{-1} \text{ arcsec}^{-1}$, respectively. The panels show the H53 α (blue) and H92 α (red) line profiles for the central $1''.8$. Each panel corresponds to a slice taken along the velocity axis of this PV diagram e.g. the panel at 0.0 is a slice along the velocity axis at offset position $0''.0$.